

Optimal Electrical Interconnection Configuration of Off-Shore Wind Farms

Mohsen Sedighi, Mohammad Moradzadeh, Osman Kukrer, Murat Fahrioglu, and Lieven Vandeveld

Abstract—Development of large-scale off-shore wind farms (OWFs) around the world has created different technical and economic challenges. Optimal configuration of the electrical interconnection of the OWFs is a key factor to minimize the investment and operational costs. This paper proposes an optimization formulation by using a Genetic Algorithm (GA) to find the optimal electrical interconnection configuration for a given OWF topology with different number of turbines. A search algorithm has been incorporated into the objective function that enumerates all feasible power flow directions from all turbines towards the power collecting hub, identifying the power flow path that minimizes the cable dimensions and thus the overall cost. The algorithm has been tested on several OWF topologies. The impact of the location of the hub has also been investigated by way of simulations. Furthermore, a comparison between single-hub and multi-hub solution has been made for multi-OWF system. The results show that multi-hub solution can be a better choice in general, especially when only the interconnection cost is compared.

Index Terms—Off-shore wind farm (OWF), optimal interconnection configuration, genetic algorithm (GA), transmission line.

I. INTRODUCTION

Off-shore Wind Farms (OWFs) are nowadays becoming a preferred solution over on-shore wind farms, to reduce the environmental implications in order to meet the high electrical power demand of modern societies [1]. In general, major difference between the cost of OWF and on-shore ones is the foundations cost, the cost of maintenance and electrical interconnection and transmission system to the shore.

In the past years, some studies aimed to find optimal interconnection configuration by addressing different power collecting systems for on-shore and off-shore wind farms. Reference [2] compares different power collecting methodologies in order to find optimal electrical configuration in on-shore wind farms by considering total cable length with minimum spanning tree algorithm. A similar study has been done in [3] for OWFs. However, they have only considered minimization of the total cable length, and thus a conventional mathematical optimization method

is often used. Since the cable dimensions between turbines are not optimized, the optimization result may leads to over-dimensioning of the cable system. References [4]-[6] and [1] have worked on optimal interconnection configuration of OWFs by using metaheuristic methods without considering cable dimensions in the optimization problem. Furthermore, the impact of the location of the power collecting hub within the farm is not investigated in most literature.

Some other studies have only investigated the optimal configuration for the transmission system which brings the OWF power to the mainland, without considering the electrical interconnection of the wind turbines within the farm [7], [8].

This paper aims to cover this gap in the literature by optimizing both the interconnecting cable dimensions and the interconnection configuration by using a Genetic Algorithm (GA), as well as illustrating the impact of the location of the hub on the overall cost. Including cable dimension in the fitness function, creates a nonlinear optimization problem (due to existence of a variable cost coefficient), thus GA is an appropriate optimization tool to be used. In this paper, the cable dimensions will be calculated for a given topology of OWF based on the actual current flowing through it. A search algorithm is proposed to identify the optimal electrical configuration associated with the minimum overall cost.

The remainder of the paper is organized as follows: In Section II a brief discussion on the cost of OWFs and Medium Voltage (MV) and High Voltage (HV) cables is provided. Section III discusses the proposed search algorithm and objective function to find the optimal electrical interconnection configuration. In next the section, in part A, the optimal interconnection configuration of three different OWF topologies, each containing 20 turbines, by two different hub locations has been shown. This section is then followed by comparing a single-hub and multi-hub solution for larger OWFs in part B. Finally, Section V summarizes the conclusions.

II. OFF-SHORE WIND FARMS (OWFs)

The control concepts and basic technology of wind turbines in both off-shore and on-shore installations are rather the same. Only the turbine size and installation cost are different. For example, acoustic emissions which are important in on-shore wind farm design are not that relevant for the OWF design. Thus, off-shore turbines can be designed for higher speed ratio, hence for the same energy output smaller turbine weight is required. On the other hand, maintenance of the OWFs is time-consuming and more difficult, requiring complex logistical operation shipments

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and mobile gear [9].

Cost is the most significant parameter in the design optimization of the OWFs. The total cost of an OWF can be expressed via the following equation:

$$C_{tot}^{OWF} = (N \times C_{turb}) + C_i + C_t + C_s^1 + C_s^2 \quad (1)$$

where:

N is the number of turbines in OWF,

C_{turb} total cost of each turbine and the internal transformer (including installation and shipping),

C_i total cost of interconnection cables (including laying and shipping),

C_s^1 total cost of off-shore substations (including installation and shipping),

C_s^2 cost of on-shore substation (including installation),

C_t total cost of transmission cables (including laying and shipping).

A. Generator and Internal Transformer

Variable-speed Doubly-Fed Induction Generators (DFIGs) and direct-drive full-scale converter generators are the most

widely-used generators for newer wind turbines. In this study, DFIG generators have been considered. Therefore, Power Factor (PF) can be set to unity ($PF = 1$) [10].

In this study, the stator output voltage of the wind turbine generator is considered to be 960 V, thus a step-up 960 V / 33 kV transformer is used to boost the voltage up to 33 kV. The output current of each turbine is calculated as:

$$I_L = \frac{P}{\sqrt{3} \cdot V_L \cdot \cos\phi} \quad (2)$$

B. Cables

In OWFs it is very important to minimize the cable costs and power losses in the interconnection turbines. Therefore, the required cable dimension between turbines will be calculated according to the actual current in this study.

In order to compare the cost of different interconnection configurations, MV cables with copper conductors (Armored XLPE Insulated) have been considered. The output voltage of the transformer of each turbine is 33 kV. The parameters of three-core copper conductors with steel wire armed cable in 33kV are shown in Table I [11].

TABLE I: MV CABLE PARAMETERS, 19/33 (36) KV

MV Cable Size (mm ²)	50	70	95	120	150	185	240	300	400
Current (A)	210	255	295	335	375	420	480	530	590
AC resistance at 90°C (Ω/Km)	0.493	0.342	0.247	0.196	0.159	0.127	0.098	0.080	0.063
Cost (€/m)	85	110	145	180	230	215	270	305	345

A 132 kV HV transmission line will be considered to connect the OWF to the mainland with the parameters of a single core Unarmored XPLE cable given in Table II.

TABLE II: HV CABLES PARAMETERS, 76/132 (145) KV

HV Cable size (mm ²)	300	400	500	630	800	1000
Current (A)	790	882	975	1066	1185	1286
AC resistance at 90°C (Ω/Km)	0.078	0.062	0.049	0.04	0.033	0.028
Cost (€/m)	350	445	520	635	770	925

Furthermore, the cost of cable laying operation is considered to be 90 €/m in this study.

III. OPTIMIZATION PROBLEM FORMULATION

A GA-based MATLAB code has been developed in this study to identify all feasible paths for power flow from each turbine to the others or to the hub.

A. Search Algorithm

In this algorithm, illustrated in Fig. 1, the power flow directions which obviously cannot be the optimal have been eliminated to reduce the computational time of the optimization. This becomes very important when the hub is located in the center of the wind farm, as it creates too many

possible paths which should be reduced to only feasible ones. Hence, only the paths which can conduct the turbine currents in shortest distance are considered.

The algorithm will take the number of the turbines within the farm (n turbines in m rows) with the hub location as input, and will output the optimal interconnection configuration such that the total cable cost (considering laying and shipping costs) as well as dimension of cables are optimized. We do this initially by allocating the hub in the center of the farm and dividing the farm into symmetric partitions. In addition, in order to decrease power losses, only 85% of nominal current has been allowed in each cable.

B. Objective Function

In order to find the optimal electrical interconnection configuration of OWFs a GA formulation has been used that considers the cable dimension of each branch individually.

The following objective function is proposed to find the optimal electrical configuration that minimizes the total cable cost:

$$\begin{aligned} \min C_{cables} &= \sum_{i=1}^N \sum_{k=1}^{M_i} (C_{c(n)} + C_{L,S(i,k)}) \cdot L_{(i,k)} \cdot x_{(i,k)} \\ \text{s.t.} \quad &\sum_{k=1}^{M_i} x_{(i,k)} = 1 \quad \forall x_{(i,k)} \in \{0,1\} \\ &\sum_{i=1}^N \sum_{k=1}^{M_i} P_{Loss(i,k)} \cdot x_{(i,k)} \leq P_{Loss}^{max} \end{aligned} \quad (3)$$

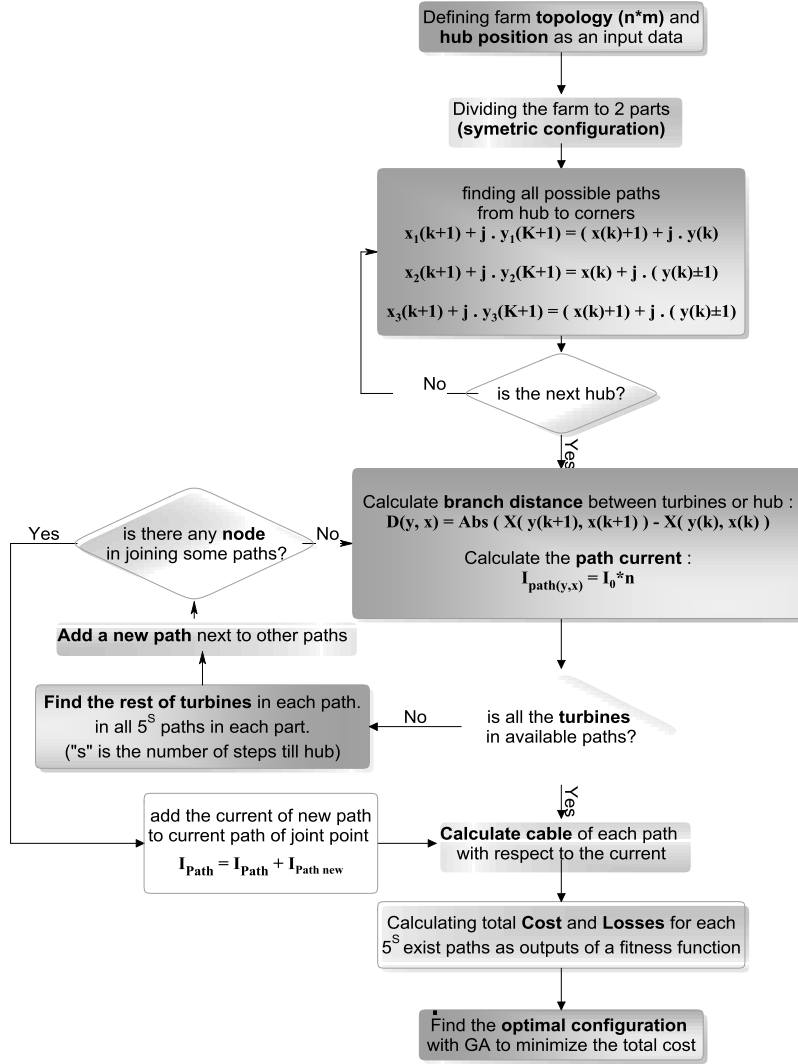


Fig. 1. Flowchart of the search algorithm to find optimal interconnection configuration in each topology.

where:

N is the number of turbines,

M_i the number of all feasible branches of i^{th} turbine,

$x_{(i,k)}$ the k^{th} feasible branch of i^{th} turbine,

$L_{(i,k)}$ the length of k^{th} branch of i^{th} turbine (m),

$C_{c(n)}$ the cost of calculated cable dimension (n) with respect to the branch current. (Euro/m),

$C_{L,S(i)}$ the laying and shipping cost of cable for k^{th} branch of i^{th} turbine (Euro/m),

P_{Loss}^{max} the maximum allowed active power losses,

$P_{Loss(i,k)}$ the active power losses for i^{th} branch (kW) which can be found from (4).

$$P_{Loss(i,k)} = (R_{(i,k)} \times I_{(i)}^2) \times L_{(i,k)} \quad (4)$$

IV. CASE STUDY

The minimum admissible distance between turbines must be larger than $4 \times D$ and larger than $7 \times D$ between rows, where D is the diameter of wind turbine blade, and the turbines in the latter row must be located exactly in the middle of the former row according to the rule of thumb [12]. Thus, in this study the distance between turbines in each row and distance between the rows are considered to

be 500 m and 750 m respectively in all topologies. Furthermore, the distance of the hub to the shore is considered to be 50 km in order to have economic justification for hub connection and using HVAC transmission line. In this study, rated power of all turbines is considered to be 5 MW in all cases.

In section A, a wind farm containing 20 turbines, is considered. In order to find the optimal location for the hub, we will consider two strategic locations for the hub, as shown in Fig. 2.

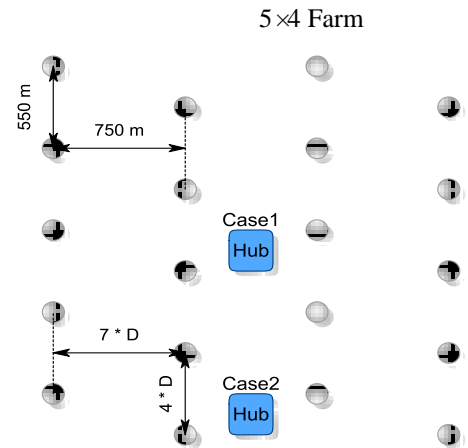


Fig. 2. A sample OWF topology with 20 turbines (5×4).

In section B, a larger OWF containing 60 turbines will be studied in order to find the optimal interconnection configuration, in single-hub and multi-hub scenarios.

A. Optimal Configuration of Internal Connection

For an OWF of 20 turbines with the total rated power of 100MW, three different topologies namely 5×4 , 7×3 ($7+6+7$) and 10×2 will be considered. Furthermore, to study the impact of hub location, two strategic points have been considered for each topology; center of the farm, and outside the farm close to the shore. Therefore, the optimal interconnection configuration minimizing the total cost will be found in two different hub locations of these three topologies.

The comparative results of both hub locations are given in Table III. The topology of 5×4 has the minimum total cable cost among other topologies in both hub locations. However, the central hub location is economically more viable in terms of investment cost as well as power losses.

TABLE III: TOTAL INTERCONNECTION CABLE COST AND LOSSES OF EACH TOPOLOGY IN BOTH HUB LOCATIONS

Hub locations	Topologies:	5×4	7×3 ($7+6+7$)	10×2
in center of OWF	Total Cable Cost + laying and shipping	2.400 M€	2.468 M€	2.861 M€
	Total Losses	133.5 KW	138.7 KW	136.4 KW
out of OWF	Total Cable Cost + laying and shipping	3.159 M€	3.684 M€	4.537 M€
	Total Losses	146.6 KW	191.1 KW	202.6 KW

Note that after finding the optimal configuration of each topology, it turns out that the total losses are negligible in comparison with the total power (100MW). Total losses in all topologies are less than 0.14%.

Fig. 3 shows the optimal interconnection configuration for topologies of a) 5×4 , b) 7×3 and c) 10×2 OWFs with 20 turbines, where the hub is located to be in the center in order to decrease the overall distance between hub and turbines.

The optimal electrical configurations of these three topologies are also found by locating the hub out of the farm, like most of recent OWFs installations. This hub location only provides an easier access for the maintenance of off-shore hub substation. Due to space limitations, only the optimal electrical configuration for topology of 5×4 has been illustrated in Fig. 4.

Note that, because of larger current flow, some branches require using more than one cable. Therefore, correction factors for such branches have been considered.

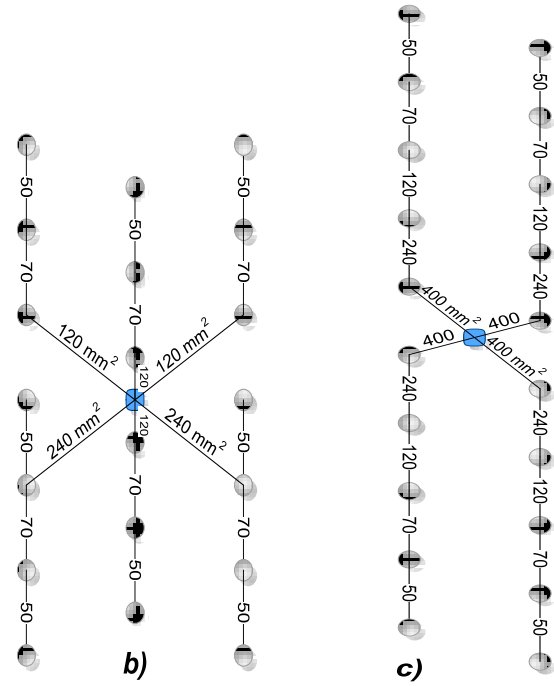
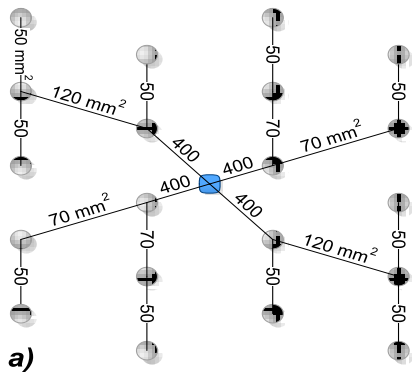


Fig. 3. Optimal configurations of 20 turbines (100MW) for three topologies: a) 5×4 , b) 7×3 and c) 10×2 , when the hub located in center.

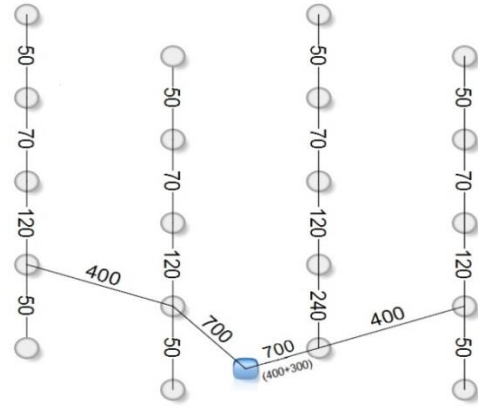


Fig. 4. Optimal configurations of 20 turbines (100MW) with topology of 5×4 , when the hub located out of OWF.

It is also important to mention that, changing the rated power of turbines or the distance between turbines in each row or between the rows may change the optimal interconnection configuration as well as the total cost in each topology. This is not investigated in this paper.

B. Single-Hub and Multi-Hub Solutions in Larger OWFs

In this section a larger size of OWF with 60 identical turbines and total rated power of 300MW is considered. The optimal electrical interconnection of the 10×6 topology in single-hub scenario is shown in Fig. 5.

This single-hub solution is also compared with a multi-hub solution, as shown in Fig. 6. In both scenarios the same number of turbines (60 turbines) with the identical rated power (5 MW) has been considered.

Scenario I is the optimal interconnection configuration of 10×6 topology with a single hub and an off-shore transformer. Scenario II divides the 10×6 topology into three 10×2 topologies with three hubs and three off-shore transformers. The comparative results of both scenarios are given in Table IV.

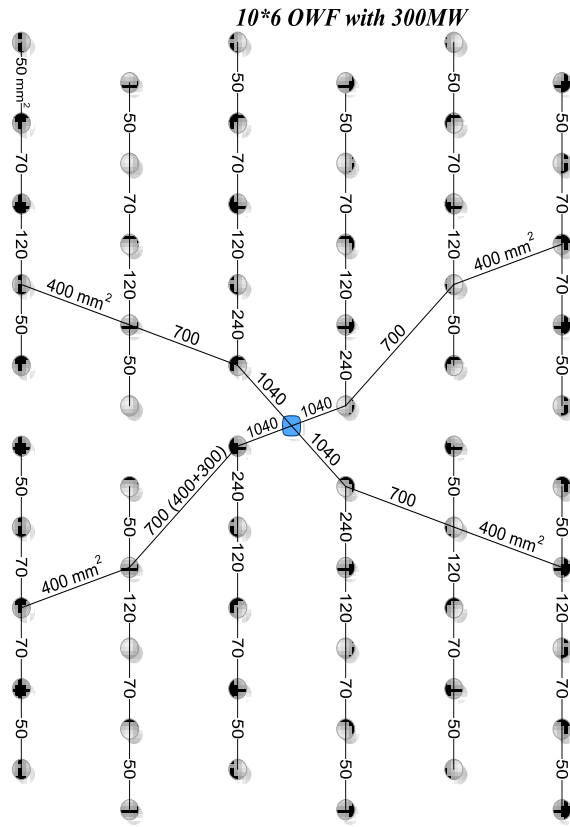


Fig. 5. Optimal configurations of a large OWF with 60 turbines (300MW) with topology of 10×6 when the hub located in center.

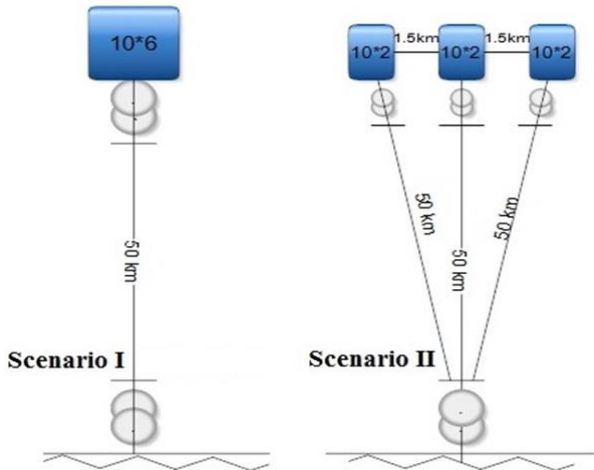


Fig. 6. Comparison between integrated OWF and three individual OWFs scenarios with same power rated and same distance to shore.

TABLE IV: COMPARISON BETWEEN SINGLE-HUB AND MULTI-HUB SOLUTIONS

	Single-Hub Farm 10×6	Multi-Hub Farm $3 \times (10 \times 2)$
Total Interconnection Losses	560 kW	$3 \times 136.4 = 410$ kW
Total Transmission Losses	6.6 MW	3.5 MW
Interconnection Cables Cost + laying and shipping	13.875 M€	$3 \times 2.861 = 8.583$ M€
Off-shore Substation (33/132 KV)	4.785 M€ (400MVA)	6.225 M€ (3x120MVA)
Transmission Cable Cost + laying and shipping (50km)	58.2 M€ (2x500 mm²)	64.5 M€ (3x300 mm²)
Total Cost	78.012 M€	78.908 M€
Total Losses	7.16 MW	3.91 MW

The results show that the total cost of the optimal configuration of 10×6 topology in single-hub solution is slightly lower than the multi-hub solution. However the total losses in multi-hub solution is 55% of total losses in single-hub solution, and the total cable cost of interconnection itself is about 62% of this amount in the single-hub solution. Furthermore, after finding the optimal electrical interconnection configuration of OWFs, the overall cost of interconnecting cables and offshore substations turned out to be very small in comparison to the total cable cost of 50 km transmission line in both scenarios. Thus, multi-hub scenario can be a preferred solution in general, especially when only the total interconnection cost is compared.

V. CONCLUSION

The significance of the optimal electrical interconnection configuration in OWFs has been the focal point in different studies. This paper proposes a search algorithm to find the optimal electrical interconnection configuration for a given OWF topology. Moreover, the cable dimension for each path has been included in the cost function to be optimized.

In order to find the optimal configuration of a given OWF topology, all feasible power flow directions have been considered for two different hub locations. The results show that the optimal configurations have minimum cost and losses when the hub is allocated at the center of the farm.

This paper also compares a single-hub solution with a multi-hub solution for a large OWF. The results show that a multi-hub solution can be a preferred choice in general, thanks to its lower total losses and lower total cost of interconnecting cables. However, single-hub solution results in a lower cost in transmission line and off-shore transformers. Furthermore, lower cost of the total interconnection cable in comparison with the total cost of transmission cable illustrates the significant impact of the optimal interconnection configuration of OWF. However, the distance of OWF to the mainland also plays an important role in the overall cost of OWF (this is not investigated in this study).

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